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Potent Immune Modulation by MEDI6383, an Engineered Human OX40 Ligand IgG4P Fc Fusion Protein

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Abstract

Ligation of OX40 (CD134, TNFRSF4) on activated T cells by its natural ligand (OX40L, CD252, TNFSF4) enhances cellular survival, proliferation, and effector functions such as cytokine release and cellular cytotoxicity. We engineered a recombinant human OX40L IgG4P Fc fusion protein termed MEDI6383 that assembles into a hexameric structure and exerts potent agonist activity following engagement of OX40. MEDI6383 displayed solution phase agonist activity that was enhanced when the fusion protein was clustered by Fc gamma receptors (FcγRs) on the surface of adjacent cells. The resulting co-stimulation of OX40 on T cells induced NF-κB promoter activity in OX40-expressing T cells and induced Th1-type cytokine production, proliferation, and resistance to regulatory T cell (Treg)-mediated suppression. MEDI6383 enhanced the cytolytic activity of tumor-reactive T cells and reduced tumor growth in the context of an alloreactive

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human T cell:tumor cell admix model in immunocompromised mice. Consistent with the role of OX40 costimulation in the expansion of memory T cells, MEDI6383 administered to healthy non-human primates elicited peripheral blood CD4 and CD8 central and effector memory T cell proliferation as well as B cell proliferation. Together, these results suggest that OX40 agonism has the potential to enhance anti-tumor immunity in human malignancies.

Keywords

MEDI6383; OX40 ligand; OX40; immunotherapy; fusion protein

Introduction

The generation of an anti-tumor immune response as a therapeutic strategy in oncology has been studied for many years. Recently, immuno-oncology drugs have demonstrated significant improvements over standard of care therapies in certain malignancies, exemplified by US Food and Drug Administration (FDA) approvals for anti-CTLA-4, anti-PD-1 and anti-PD-L1 monoclonal antibodies (mAb) (1). Despite this success, a significant number of cancer patients do not respond to immunotherapies, respond incompletely, or discontinue therapy due to adverse events. Immunosuppressive mechanisms outside of the targeted pathway may prevent an effective anti-tumor immune response within the tumor microenvironment (TME) despite the presence or recruitment of anti-tumor T cells (2). Such factors include suppressive immune cells that include regulatory T cells (Treg) and myeloid-derived suppressor cells (MDSC) capable of suppressing activated T cells. Therefore, additional therapies are needed that expand high affinity, tumor-specific T cells in regional draining lymph nodes or within the TME despite immunosuppression not currently addressed by immunologic checkpoint blockade.

One strategy to promote an anti-tumor immune response that is different from checkpoint inhibition is to activate the TNF receptor superfamily (TNFRSF) of co-stimulatory T cell receptors. Agonist approaches for these receptors currently undergoing clinical trials include antibodies and other technologies targeting CD137 (4-1BB; TNFRSF9), CD40 (TNFRSF5), CD27 (TNFRSF7), GITR (CD357; TNFRSF18), and OX40 (CD134; TNFRSF4) (3). OX40 is a TNFRSF member expressed on activated effector and memory, as well as regulatory, T cells. Development of the mouse mAb 9B12, subsequently termed MEDI6469, was the first anti-human OX40 mAb in clinical development for advanced solid malignancies, and showed encouraging anti-tumor responses and a tolerable safety profile (4). The mouse origin of the MEDI6469 antibody, however, limits its clinical utility to one cycle of treatment due to the emergence of human anti-mouse antibody (HAMA) responses. Subsequently, a humanized version of MEDI6469 termed MEDI0562 was created to avoid the immunogenicity seen with MEDI6469. This and other agonist anti-human OX40 mAbs have entered early phase clinical testing (5–7).

OX40-specific mAbs, as bivalent OX40 binding moieties, have the potential to induce OX40 signaling when clustered, but have not been shown to be capable of trimerizing OX40 in the absence of clustering. In contrast, the naturally trimeric OX40 ligand (OX40L, CD252, TNFSF4) protein complex expressed by professional antigen-presenting cells (APCs) can trimerize OX40 directly. The engagement of OX40 by the OX40L, in concert with other co-stimulatory signals, promotes T cell activation, survival, expansion, and the formation of effector and central memory T cell pools. In contrast to OX40-specific mAbs, engineered fusion proteins containing the OX40L extracellular domain (ECD) have been created to take advantage of the strong agonist properties of the ligand. Previously, a human OX40L ECD linked to a human IgG1 Fc domain via a coiled-coil trimerization domain from the yeast GCN4 protein had been expressed and characterized (8). It was found to naturally associate into a hexameric human OX40L fusion protein structure composed of two trimerized molecules covalently bound together through disulfide linkages found in the human IgG1 Fc domains.

To build a hexameric human OX40L fusion protein suitable for clinical use, we designed a fully human OX40L fusion protein termed MEDI6383. This protein contains human OX40L ECDs fused to the trimerization domain of the human TRAF2 protein and to human IgG domains to enable the formation of a covalently linked hexamer. Because the human IgG1 isotype can mediate complement fixation and antibody-dependent cellular cytotoxicity (ADCC), we chose human IgG4 as the human IgG isotype to minimize the possibility of in vivo depletion of OX40-expressing effector T cells. Although human IgG4 was unlikely to mediate ADCC or complement fixation, this isotype can bind with relatively lower affinity to human FcγRs other than CD16 (9), which may be enhanced by avidity effects. Therefore, we were interested to test whether FcγR-mediated clustering may enhance MEDI6383 activity.

Based on the structure of the molecule, we further hypothesized that MEDI6383 would lack effector function, induce potent CD4 T cell activation and expansion both in vitro and in vivo, and mediate anti-tumor immunity in animal models. Likewise, we hypothesized that MEDI6383 would protect conventional CD4 T cells from Treg-mediated suppression as has been reported for other OX40 agonists. In this manuscript, we report the production and characterization of MEDI6383 and the testing of these hypotheses using human in vitro assays and after the administration of MEDI6383 to immuno-deficient mice bearing an admixture of human T cells and tumor cells as well as to healthy rhesus macaques. Results from these studies show that MEDI6383 represents an attractive candidate to activate and expand tumor-reactive T cells in patients with cancer.

Materials and Methods

OX40 binding molecules and control reagents

MEDI6383 was generated by genetically recombining DNA fragments that encode the human IgG4P fragment crystallizable (Fc) domain, the human tumor necrosis factor receptor-associated factor 2 (TRAF2) coiled coil domain (10), and the human OX40 ligand (OX40L) extracellular receptor binding domain (RBD). The control fusion protein lacking binding to OX40, termed F180A OX40L fusion protein control, was generated by mutating phenylalanine at position 180 to alanine which is known to abrogate OX40L binding to OX40 (11). MEDI6469 is a mouse anti-human OX40 mAb previously termed 9B12 and described previously (4).

Analytical size-exclusion chromatography

MEDI6383 protein sample was applied onto a TSK-gel G3000SWxL column (Tosoh Biosciences, Tokyo, Japan), eluted isocratically with an Agilent 1200 HPLC system (Agilent Technologies, Santa Clara, CA), and detected using UV absorbance at 280 nm and DAEN EOS Multi-Angle Light Scattering (MALS) (Wyatt Technology, Santa Barbara, CA).

Cell Lines, tissue culture reagents and culture conditions

All cell lines were originally purchased from the American Type Culture Collection (ATCC) and tested at Medimmune for mycoplasma using mycoplasma-specific real-time PCR prior to use. Human A375 melanoma, Raji B, and HEK293 parental cells were authenticated by short tandem repeat profiling (IDEXX BioResearch Laboratories, Westbrook, ME); human OX40-expressing Jurkat NFκB-luciferase reporter cells did not undergo cell line authentication. All cells except those used in regulatory T cell (Treg) suppression assays were cultured in RPMI complete media consisting of RPMI-1640 containing supplements (Life Technologies, Carlsbad, CA; catalog# A1049101) plus 10% v/v heat inactivated fetal bovine serum (FBS) and 1% v/v (1X) penicillin/streptomycin antibiotics (Life Technologies) in a humidified tissue culture incubator at 37°C and 5% CO_2. T cells in Treg suppression assays were cultured in RPMI-1640 Glutamax-I (Life Technologies, catalog # 61870-036) containing 1% v/v Penicillin and Streptomycin, 5% v/v human AB serum and 1 μg/mL anti-CD28 antibody, clone 28.8 (BD Biosciences, San Jose, CA).

Flow cytometry reagents and analysis

Bovine serum albumin (BSA) and propidium iodide (PI) were purchased from Sigma-Aldrich (St. Louis, MO). OX40 was detected using APC-conjugated anti-human OX40 clone Ber-ACT35 (Biolegend). Flow cytometry data was collected by a BD LSRII flow cytometer (Becton Dickinson, Franklin Lakes, NJ) and flow cytometry standard (fcs) data analyzed using Flowjo software (Flowjo LLC, Ashland, OR). Absolute CD4 and CD8 cell counts for the rhesus macaque study were generated using TruCount Beads (Becton Dickinson) and is described further in Supplementary Methods.

Binding of MEDI6383 and MEDI6469 to activated human CD4 T cells

Primary human CD4+ T cells were obtained through negative selection of PBMC isolated from sodium heparin anti-coagulated whole blood from healthy human or non-human primate (NHP) donors. CD4 T cells were cultured with 2 μg/mL phytohemaglutinin-leucoagglutinin (PHA-L; Roche Life Sciences, Indianapolis, IN) and 20 IU/mL recombinant human IL2 (rhIL2; PreproTech, Rocky Hill, NJ) to activate T cells and up-regulate OX40. Activated T cells expressing OX40 were bound to MEDI6383 or MEDI6469 and detected with AlexaFluor®647-conjugated or AlexaFluor®488-conjugated goat anti-human IgG secondary antibody (Life Technologies) on live (PI negative) cells. The apparent (avidity driven) equilibrium binding constants for MEDI6383 or MEDI6469 binding were determined after background subtraction using GraphPad Prism version 5.01 for Windows (GraphPad Software, La Jolla, CA) with a non-linear regression equation for one site, specific binding.

NFκB luciferase reporter T cell assays

For NFκB luciferase reporter T cell assays, human Jurkat T cells were engineered to constitutively express human OX40 and to produce luciferase upon induction of tandem NFκB promoter elements upstream of luciferase. The Jurkat NFκB-luciferase reporter cell line was in some cases used together with an FcγR-expressing cell line at a 1:1 ratio (100,000 reporter cells plus 100,000 FcγR-expressing cells) for clustering of MEDI6383 or MEDI6469 in trans through Fc domain clustering. FcγR-expressing CD45+ cells from primary human tumors were isolated using a human CD45 microbead positive selection kit (Miltenyi Biotec, Auburn, CA) from tumors digested to single cell suspensions as described in Supplementary Methods. Luciferase production was measured using the SteadyGlo luciferase assay system (Promega, Madison, WI) and a Perkin Elmer Envision multi-label micro plate reader (Molecular Devices, Sunnyvale, CA). FcγR-blocking reagents and controls used to demonstrate FcγR-dependent activity in 2-cell reporter bioassays included: bovine serum albumin (Sigma-Aldrich), hexameric GITRL fusion proteins containing human IgG1 (control hexamer IgG1) or human IgG4P (control hexamer IgG4P) Fc domains (12,13) that do not bind OX40 or activate OX40 reporter cells but can compete with MEDI6383 for FcγR binding (generated at MedImmune), LEAF™ purified mouse IgG1 κ isotype control antibody clone MOPC-21 (Biolegend), LEAF™ purified mouse anti-human CD64 antibody clone 10.1, sterile PBS-dialyzed purified mouse anti-human CD32 antibody clone FUN-2 (Biolegend), purified human IgG gamma globulin (Jackson Immunoresearch, West Grove, PA), and sterile human AB serum (Thermo Fisher Scientific, Waltham, MA). These reagents were added to 2-cell bioassays containing parental or FcγR-expressing HEK293 cells, as indicated, for 45 minutes prior to addition of 0.5 μg/mL (1.6 nM) MEDI6383 and OX40 Jurkat NFκB-luciferase reporter cells to allow for effective competition for FcγRs.

Primary human T cell bioactivity assays

Enriched human CD3, CD4, or CD8 T cells were isolated from healthy donor Leuko Paks (AllCells, Alameda, CA) or whole blood (MedImmune Blood Donor Program) using EasySep™ human (CD3) T cell, CD4, or CD8 T cell enrichment kits (for leuko paks; Stemcell Technologies, Vancouver, Canada) or RosetteSep™ human T cell enrichment cocktail (CD3), RosetteSep™ CD4 or RosetteSep™ CD8 T cell enrichment cocktail (for whole blood; Stemcell Technologies). Thereafter, T cells were activated using 2 μg/mL PHA-L and 20 IU/mL rhIL2 for 48 hours to up-regulate OX40. To test the ability of plate-immobilized MEDI6383 to induce cytokine secretion and T cell proliferation, activated OX40-expressing T cells were added to non-tissue culture-treated round-bottom 96 well assay plates to which MEDI6383 and a sub-optimal concentration (2 ng/mL) of UltraLEAF™ low endotoxin clone OKT3 anti-human CD3 monoclonal antibody (mAb) (Biolegend) had been immobilized. For wells containing solution phase MEDI6383, antibody-based capture of MEDI6383 was omitted. Cells were labelled with carboxyfluorescein succinimidyl ester (CFSE) using the CellTrace™ CFSE cell proliferation kit (Life Technologies) and cell proliferation at 72 hours measured by CFSE dilution. Cytokine release at 72 hours was measured using Mesoscale Discovery (MSD) Th1/Th2 10-plex tissue culture kit (MesoScale Diagnostics, Rockville, MD).

To test the activity of MEDI6383 clustered by CD32A-expressing HEK cells, fusion protein was incubated with isolated, activated and CFSE-labeled primary human CD3, CD4, or CD8 T cells plus CD32A-expressing HEK cells together with 10 µg/mL of the anti-CD3 mAb clone OKT3 to initiate T cell receptor (TCR) stimulation.

Natural Treg suppression assay

Human CD4 effector T cells (Teff) and regulatory T cells (Treg: $CD4^{+}CD25^{high}CD127^{low}$) were isolated from the same healthy donor Leukopacks (Hemacare, Los Angeles, CA) using an EasySep human $CD4^{+}$ T cell isolation kit and a EasySep human $CD4^{+}CD127^{low}CD25^{high}$ Regulatory T cell isolation kit (Stemcell Technologies), respectively (see Supplementary Figure 1 for CD25, CD127 and FoxP3 immunophenotypic profile). Teff were labeled with CFSE using the CellTrace™ CFSE cell proliferation kit and Treg with the CellTrace™ Violet cell proliferation kit (Thermo Fisher Scientific, Waltham, MA). Teff and Treg were cocultured at 1:1 ratio in complete RPMI1640 medium containing 5% v/v human AB serum and 1ug/ml Purified NA/LE anti-CD28 mAb, clone 28.2 (BD Biosciences) in the tissue culture plates coated with anti-human CD3 clone OKT3 (Biolegend) alone or with MEDI6383 or F180A OX40L fusion protein control. After 5 days of co-culture in a humidified tissue culture incubator at 37°C and 5% CO_2, the percentages of divided CD4 Teff cells (CFSE dilution) and divided CD4 Treg cells (CellTrace™ Violet dilution) were assessed by flow cytometry on an Fortessa flow cytometer (Becton Dickinson) and using Flowjo Software (Flowjo LLC).

Human T cell/tumor cell admixed xenograft model

NOD/SCID mice of 5-9 weeks of age were purchased from Envigo Harlan Laboratories, Inc. (Indianapolis, IN). Studies with mice were conducted in accordance with and approved by the Institutional Animal Care and Use Committee-approved protocols in the Laboratory Animal Resources facility at MedImmune, an Association for Animal Accreditation of Laboratory Animal Care and United States Department of Agriculture-licensed facility.

Human CD4 and CD8 T cells were separately isolated from healthy donor peripheral blood using CD4 and CD8 human T cell enrichment kits (Stemcell Technologies). To generate A375 melanoma tumor cell line-reactive CD4 and CD8 lines, enriched CD4 and CD8 T cells were cultured separately in RPMI complete media containing rhIL2 with mitomycin C-treated A375 tumor cells for one week. T cells were collected and separately re-stimulated with mitomycin C treated A375 tumor cells and rhIL2 again for an additional week. Expanded CD4 and CD8 T cell lines were combined at a 2:1 ratio and then added to A375 tumor cells to produce a ratio of 6:1 of A375 to total T cells, and a total of 3.5×10^6 cells were injected into the flank of NOD/SCID mice. MEDI6383 or a control OX40L IgG4P fusion protein containing an F180A point mutation (phenylalanine replaced by alanine at position 180) in the OX40 binding interface that abrogates OX40L:OX40 interactions (11) was injected at the indicated doses levels and times starting at day 3 after admixed tumor cell/T cell engraftment. Dosing was continued 2 times per week for 2 weeks. Tumor dimensions were measured using a caliper at the indicated time points and tumor volumes calculated using the following formula: V (mm^3) = (length [mm] × width [mm] × width [mm])/2. Antitumor effects were expressed as percent tumor growth inhibition (% TGI), which was calculated as follows: % TGI = (1 – [mean tumor V of treatment group] ÷ [mean tumor V of control group]) × 100.

MEDI6383 administration to rhesus macaques

Indian-origin rhesus macaques (*Macaca mulatta*) were housed at the Oregon National Primate Research Center and experiments with these animals were conducted in accordance with and approved by the Institutional Animal Care and Use Committee for Oregon Health & Science University/Oregon National Primate Research Center and the Guide for the Care and Use of Laboratory Animals. Vehicle control (sterile PBS), MEDI6383, or mouse anti-human OX40 mAb MEDI6469 (previously termed 9B12) were administered via the intravenous (bolus) route (n=5 female macaques per group). Vehicle and MEDI6383 at 1 mg/kg were administered every other day (Day 0, 2, and 4) for a total of 3 doses while MEDI6469 was administered as a single 5 mg/kg dose. Following test article administration, Anticoagulant Citrate Dextrose (ACD) anticoagulated peripheral whole blood was collected at the indicated times for immuno-phenotyping by whole blood staining. Antibody panels used to stain rhesus peripheral immune cells for flow cytometry analysis are shown in Supplementary Figure 2A, with Ki67 antibody included in intracellular Ab cocktails and the remainder added to surface antibody cocktails. Example gating of total, central, and effector memory CD4 or CD8 T cells based on CD95, CD28, CCR5 and CCR7 staining is shown in Supplementary Figure 2B.

Statistical analyses

Statistical differences between proliferation values for MEDI6383-mediated Teff proliferation in the presence or absence of Treg were determined using unpaired, two-tailed Student’s t test. Differences between tumor growth in MEDI6383-treated and isotype control-treated animals bearing A375 tumors from A375/human T cell admixtures were analyzed for statistical significance by a Mann-Whitney rank sum test. Differences between experimental conditions in Fcγ R-expressing HEK293 2-cell bioassays using Fcγ R blocking reagents and for pharmacodynamic measurements between baseline (day 1 pre-dose) and indicated time points in the rhesus study were analyzed for statistical significance using one-way analysis of variance (ANOVA) with Dunnett’s post-test correction for multiple comparisons, reporting multiplicity adjusted P values for each comparison using GraphPad Prism version 7.02 (GraphPad Software). Differences between MEDI6383-treated or F180A OX40L FP control-treated conditions in Treg assays were analyzed by two-tailed Student’s t-test using GraphPad Prism.

Results

Design and preparation of MEDI6383

MEDI6383 was designed as a human OX40L IgG4P Fc fusion protein composed of three distinct domains: (1) human OX40 ligand extracellular receptor binding domains (RBD) that form homotrimers and bind OX40; (2) isoleucine zipper coiled coil domains derived from TRAF2 (10) that stabilize the homotrimeric structure of the OX40L RBDs; and (3) human IgG4 fragment crystallizable gamma (Fc) domains that facilitate Fcγ receptor clustering of the fusion protein and contain a serine to proline substitution in the hinge regions at position

228 according to EU numbering of the full length IgG4 heavy chain sequence (IgG4P) to prevent inter-Fc strand exchange (Figure 1A). The resulting protein has a calculated molecular mass of 306,000 daltons supportive of a glycosylated, hexameric protein. Size exclusion chromatography (SEC) and SEC-MALS suggested a highly purified hexameric form (Figure 1B) with an apparent molecular mass of 330,000 daltons, consistent with the calculated mass (Figure 1C).

MEDI6383 potently binds OX40 on activated primary human and NHP T cells

After purification, MEDI6383 was tested for binding to native OX40 on the surface of activated human and NHP T cells. We found that OX40 is highly expressed on activated CD4 T cells as opposed to activated human CD8 T cells (Supplementary Figure 3A and 3B). Therefore, we used activated primary human and NHP CD4 T cells for binding studies. Results showed potent binding to OX40 on activated human, cynomolgus, and rhesus CD4 T cells, with mean apparent equilibrium binding constant (K_D) values of 1.7, 24, and 21 pM, respectively (Supplementary Figure 3 and Supplementary Table 1). The control OX40L fusion protein containing an F180A point mutation (phenylalanine replaced by alanine at position 180) in the OX40L binding interface that abrogates OX40L:OX40 interactions (11) did not demonstrate appreciable binding to human or non-human primate OX40. MEDI6383 binding to OX40 was substantially more potent than that of the mouse anti-human OX40 mAb MEDI6469. The latter bound to activated human CD4 T cells with a mean apparent K_D value of 669 pM (Supplementary Table 1).

MEDI6383 induces NFκB signaling in human T cells that is enhanced by Fcγ receptor-mediated drug clustering

To demonstrate the ability of MEDI6383 to induce OX40-mediated signaling in human T cells, we generated T cell reporter and drug clustering cell lines for use in a series of in vitro bioactivity potency assays. First, we created an OX40-expressing Jurkat human T cell reporter line infected with a lentivirus directing the OX40-inducible expression of luciferase from an NF-κB promoter. Second, we made HEK293 cell lines engineered to express either the human Fcγ receptor CD32A (FcγRIIA H131, with histidine at position 131), CD64 (FcγRI), or CD16 (FcγRIII 158F or 158V, with phenylalanine or valine at position 158) to evaluate the potential of Fc domain based clustering of MEDI6383 to enhance drug activity (Supplementary Figure 4). Upon ligation of OX40 on the NFκB-luciferase Jurkat reporter cell line, luciferase enzyme activity is produced in the reporter cells through NFκB promoter activation and can be measured as a bioluminescent readout (Figure 2A). As was observed for primary human T cells, MEDI6383 showed potent binding to OX40 expressed exogenously on the NFκB-luciferase Jurkat T cell reporter line with an apparent K_D of 4.9 pM (Supplementary Table 1). After the addition of MEDI6383, moderate NFκB promoter activation was observed in a dose-dependent manner, demonstrating that solution-phase MEDI6383 is capable of mediating low levels of OX40 clustering on reporter cells (Figure 2B). No change in this activity was observed after the addition to the assay of parental HEK293 human embryonic kidney cells that lack FcγR expression. However, the activity was significantly enhanced in a dose-dependent manner when the reporter Jurkat cells were co-incubated with MEDI6383 and HEK293 cells expressing CD32A or CD64 (Figure 2C and 2D), but not CD16 (supplementary Figure 4H and 4I). This demonstrated that OX40 receptor agonism by MEDI6383 occurred to a limited extent in a solution phase form that was enhanced when MEDI6383 was clustered by binding of Fc domains on the fusion protein to FcγRs on the surface of CD32A- or CD64-expressing HEK293 cells.

To further demonstrate the dependency of the clustering on FcγRs, FcγR blocking reagents and appropriate control proteins were used in 2-cell bioassays with FcγR-expressing HEK293 cells, reporter cells and MEDI6383 at a concentration (0.5 μg/mL; 1.6 nM) to induce optimal activity. With HEK293 parental cells in the 2-cell reporter bioassay, none of the FcγR blocking reagents affected the minimal solution-phase activity of MEDI6383 except human serum which slightly, but statistically significantly, enhanced bioactivity (Figure 2E). In contrast, control hexamer fusion proteins of human IgG1 and IgG4P isotypes used in excess to MEDI6383 or an anti-CD32 mAb significantly inhibited drug activity mediated by HEK CD32A drug clustering, with the strongest inhibition observed for the IgG1 isotype control hexamer fusion protein and the anti-CD32 mAb (Figure 2F). Human serum at ten or twenty percent of assay volume did not significantly affect activity, nor did purified human IgG at 100 μg/mL. Likewise, the control hexamer fusion proteins of human IgG1 and IgG4P isotypes and an anti-CD64 mAb significantly inhibited MEDI6383 mediated bioactivity when HEK CD64 cells were used, with the IgG1 isotype control hexamer consistently showing the greatest activity (Figure 2G). In this format, however, ten or twenty percent human serum also decreased MEDI6383 activity, albeit reproducibly less than that of the control hexamer fusion proteins or anti-CD64 mAb. Purified human IgG at 100 μg/mL did not affect activity of MEDI6383 with HEK CD64 cells. In total, these results demonstrate that MEDI6383 bioactivity was mediated by FcγR clustering in this bioassay format.

To test whether FcγR-mediated enhancement of MEDI6383 activity may occur in the context of FcγR clustering by Raji tumor B cells (predominately expressing CD32B, see Supplementary Figure 4) or by CD45 immune cells isolated from primary tumors (in total expressing CD64, CD32A, CD32B, and CD16; Supplementary Figure 4), we tested these cell types in 2-cell bioassays. Results showed that both cell types mediated robust MEDI6383 activity, greater than that observed for MEDI6383 in the absence of clustering (Figure 2H, 2I and 2J). The F180A OX40L fusion protein control lacking the ability to bind OX40 did not demonstrate activity in any of the 2-cell assays tested. MEDI6469 bound with lower apparent affinity than MEDI6383 to OX40 on the surface of Jurkat reporter cells (apparent K_D of 922 pM; Supplementary Table 1). Likewise, MEDI6469 had a substantially lower potency than MEDI6383 for OX40 reporter activity in the 2-cell bioassay format when utilizing either Raji or CD32B-expressing HEK cells to cluster drug (Supplementary Table 2).

Multiple FcγRs were capable of mediating enhanced MEDI6383 activity except CD16, an FcγR expressed by NK cells that mediates NK cell-mediated cytotoxicity when effectively cross-linked by antibodies with an appropriate isotype (i.e., human IgG1) (14). Therefore, we sought to determine whether MEDI6383 was capable of inducing NK cell ADCC of OX40-expressing cells. MEDI6383 contains six Fc domains of the IgG4 class, and thus the fusion protein would not be expected to mediate ADCC by CD16-expressing NK cells. As predicted, MEDI6383 did not demonstrate ADCC when added to mixtures of primary human NK cells and CD4 T cells expressing high levels of OX40, whereas an IgG1-formatted version of MEDI6383 (OX40L fusion protein IgG1) demonstrated potent NK cell-mediated ADCC activity (Supplementary Figure 5A). Furthermore, MEDI6383 did not bind the complement component C1q (Supplementary Figure 5B). This suggests that it would not mediate complement-dependent cytotoxicity of OX40-expressing cells.

Induction of cytokine release and proliferation in activated primary human T cells by MEDI6383

Results using the OX40-expressing Jurkat reporter T cells suggested that MEDI6383 would potentiate primary human T cell activation. To test this hypothesis, primary human CD3+ T cells were isolated from healthy donors, activated with PHA-L plus IL2 to up-regulate cell surface expression of OX40, and then plated onto tissue culture plates coated with a sub-optimal T cell receptor (TCR) stimulus (plate-bound anti-human CD3 mAb clone OKT3) and a range of concentrations of MEDI6383 (Figure 3A). The F180A OX40L fusion protein control was included to demonstrate OX40-specific effects. The immobilized MEDI6383 induced the release of 5-fold or higher IFNγ and TNFα levels from activated primary human CD3-purified T cells in a concentration-dependent manner (Figure 3B and 3C) and at least 2-fold or higher levels of IL10, IL13, IL5, and IL8 (Supplementary Figure 6), suggesting that MEDI6383 can induce the release of Th1 and Th2-type cytokines under these culture conditions. Likewise, MEDI6383 induced CD4 T cell proliferation among activated CD3 purified T cells in a concentration-dependent manner (Figure 3D). The F180A OX40L fusion protein control did not induce cytokine release or proliferation, showing that the effects were specific to OX40 engagement. Interestingly, solution phase MEDI6383 (i.e., drug not pre-immobilized to the assay plate) did not induce cytokine release or proliferation under these experimental conditions. There was also a lack of MEDI6383-induced cytokine release and proliferation in the absence of concomitant TCR stimulation (no anti-CD3 mAb).

Consistent with its enhancement of T cell cytokine release and proliferation, co-stimulation with MEDI6383 enhanced the expression levels of the T cell activation markers CD137, CD30, PD-1 and CD25 on activated CD3 T cells (Supplementary Figure 7). The increase in cell surface markers occurred on both CD4 and CD8 T cell subsets, indicating that MEDI6383 engaged low levels of OX40 on CD8 T cells or that cross-talk between OX40-expressing CD4 T cells and CD8 T cells occurred in co-culture conditions. Taken together, these results showed that MEDI6383 further enhanced activation of both CD4 and CD8 T cells when present in the same experimental conditions.

To examine the activity of MEDI6383 with activated primary human T cells in the context of FcγR clustered drug together with sub-optimal TCR (anti-CD3) stimulation, MEDI6383 was tested in a variation of the 2-cell bioassay using activated primary human T cells. In this assay drug-clustering HEK cells expressing CD32A were tested with isolated primary human CD3, CD4, or CD8 T cells activated with PHA-L plus IL2 to up-regulate cell surface expression of OX40. Consistent with results from bioassays using plate-immobilized drug, MEDI6383 induced a concentration-dependent increase in CD4 T cell proliferation among purified, activated CD4 T cells (Figure 3E) or CD3 T cells (Supplementary Figure 8) when incubated with CD32A-expressing HEK and anti-CD3 mAb. No enhancement of proliferation was observed among CD4 T cells in the absence of HEK CD32A-expressing cells or in the absence of anti-CD3 stimulation, demonstrating the requirement for drug clustering and TCR stimulation to induce a MEDI6383-mediated biological response.

Overall, experiments using activated primary human T cells demonstrated TCR signal-dependent co-stimulatory activity of MEDI6383 upon drug clustering, but not in solution phase. CD4 cells express higher activation-induced OX40 on cell surfaces than CD8 cells (Supplementary Figure 3A and 3B), and MEDI6383 demonstrated potent and consistent enhancement of activity among these cells, and less potent and inconsistent enhancement of primary CD8 T cell activation.

MEDI6383 inhibits nTreg-mediated suppression of conventional T cells

MEDI6383 augmented the activation of conventional CD4 T cells, but in the immunosuppressive tumor microenvironment the activity of T cells can be dramatically suppressed (2). Natural or induced regulatory T cells (nTreg or iTreg, respectively) represent two related but distinct cell types that may mediate inhibition of conventional T cell activation through cell-to-cell contact-mediated mechanisms as well as by soluble factors (15). To examine the ability of MEDI6383 to overcome nTreg inhibition of conventional T cell activation, we co-cultured TCR-stimulated conventional CD4 T cells with MEDI6383 in the absence and presence of autologous nTreg cells isolated from healthy donor peripheral blood (Figure 4; Supplementary Figure 1). Freshly isolated conventional CD4 (Teff) and Treg cells expressed low but detectable OX40 that was up-regulated upon Teff plus Treg co-culture in the presence of anti-CD3 and anti-CD28 stimulation (Figure 4A). As had been shown above, MEDI6383 promoted TCR driven T cell proliferation in the absence of nTregs. In the presence of nTregs proliferation was inhibited. The nTreg mediated inhibition of Teff proliferation was reversed to levels observed in the absence of nTregs when nTreg plus Teff cells were cultured in the presence of MEDI6383, demonstrating the ability of the fusion protein to prevent Treg immunosuppression of Teff cell proliferation (Figure 4B and D). Treg cells themselves proliferated poorly when cultured alone. However, Tregs cultured alone were induced to proliferate by MEDI6383 in a concentration-dependent manner, but not by the F180A OX40L FP control (Figure 4C and E). When co-cultured with Teff cells, a greater percentage of Treg cells proliferated at baseline (~ 30%) than when cultured alone (< 10%). As when Treg were cultured alone, MEDI6383 induced the proliferation of Treg cells in a concentration-dependent manner when Treg cells were co-cultured in the presence of Teff cells. In total, these results show that MEDI6383 induces the proliferation of both Teff and Treg cells cultured alone or in co-culture with one another.

MEDI6383-mediated anti-tumor activity in vivo

Testing the activity of MEDI6383 in immunocompetent mouse syngeneic models is not possible since human OX40L binds to human and primate OX40 but not to mouse OX40. Therefore, to determine if agonism of OX40 by MEDI6383 could help anti-tumor T cells overcome the immune-suppressive environment within a tumor, we tested the ability of MEDI6383 to mediate tumor clearance in vivo using a human tumor/T cell admixed model. In this model, human CD4 cells that express OX40 on their cell surface (Supplementary

Figure 9) and CD8 T cells that are each alloreactive to the human melanoma cell line A375 were mixed with A375 melanoma cells and implanted into the flank of NOD/SCID mice. Thereafter, mice were treated with isotype F180A OX40L fusion protein control or MEDI6383 at various dose levels and anti-tumor effects were monitored. Administration of MEDI6383 to tumor-bearing mice caused significant tumor growth inhibition when compared to control fusion protein-treated mice (Figure 5A). This effect was dependent on the activity of T cells as no growth inhibition was observed in their absence, but was restored upon addition of T cells to the admixture (Figure 5B and 5C).

Induction of immune cell activation by MEDI6383 administered systemically to NHP

MEDI6383 at 1 mg/kg was administered by the intravenous route every other day for three injections in five rhesus monkeys (Figure 6A). Vehicle (PBS) control or a single 5 mg/kg bolus injection of the mouse anti-human OX40 mAb MEDI6469 was administered to separate cohorts of five monkeys each for comparison to MEDI6383 (Figure 6A). Whole blood was obtained at various time points prior to and after drug administration for immunophenotyping of peripheral blood populations. After MEDI6383 administration, the percentages of total memory CD4 T cells positive for Ki67 (proliferating CD4) increased from a baseline of 7% (day 0 pre-dose) to 52% at day 10 post-dose (>7-fold increase, p=0.003) (Figure 6B). Smaller, but statistically significant, increases in the percentages of proliferating total memory CD8 T cells were also seen, rising from 9% at baseline (day 0 pre-dose) to 19% at day 10 post-dose (>2-fold increase, p=0.02). In contrast, no increases in proliferation among vehicle-treated or of treated naïve CD4 or CD8 T cells were observed, which remained low throughout the study. Subdividing total memory cells into central (Tcm) and effector memory (Tem) subsets yielded different proliferation profiles among each subset. For CD4 memory T cells, an increase in proliferating CD4 Tcm cells from 5% at day 0 pre-dose to 56% at day 10 (>10-fold, p=0.001) was observed, whereas a smaller increase in proliferating CD4 Tem cells was detected with 7% at day 0 pre-dose and 14% at day 14 (~2-fold, p=0.005), reaching a maximum level later than CD4 Tcm cells (day 14 versus day 10). For CD8 memory T cells, the magnitude of the Ki67 increase among CD8 Tcm cells was smaller than that observed for CD4 Tcm, with 6% at day 0 pre-dose and 29% at day 10 (5-fold, p=0.02). The increase for CD8 Tem was similar to that for CD4 Tem, with 11% at day 0 pre-dose and 21% at day 14 (~2-fold, p=0.02). The kinetics of peak Ki67 induction in the CD8 Tem population (day 14) was delayed relative to that observed in the CD8 Tcm subset (day 10), similar to what was observed for CD4 memory populations. The induction of CD4 memory T cell proliferation by MEDI6383 was greater than that observed for MEDI6469 among CD4 total memory (11% at day 0 pre-dose to 27% at day 10, ~2.5-fold, p=0.03) CD4 central memory (9% at day 0 pre-dose to 23% at day 10, ~2.5 fold, p=0.02) and CD8 central memory T cells (9% at day 0 pre-dose to 13% at day 7, ~1.5-fold, non-significant at p=0.29). This result was perhaps expected given the higher binding affinity of MEDI6383 for OX40 relative to that of MEDI6469 (Supplementary Table 1) and the relatively greater potency observed for the fusion protein in 2-cell bioactivity assays with FcγR-expressing cells (Supplementary Table 2).

We evaluated markers of T cell activation and found an increase in the percentage of ICOS+ total memory CD4 (2% at day 0 pre-dose to 15% at day 7, ~7-fold, p=0.01) and total memory CD8 T cells (0.7% at day 0 pre-dose to 3% at day 7, ~4-fold, p=0.01), reaching maximum levels around day 7-10 (Figure 6C). The greatest percentage of the responding cells was higher in CD4 versus CD8 memory cells, but at lower percentages overall when compared with the Ki67 positive fraction of total memory cells at those time points (Figure 6B). Increases in the percentage of PD-1+ CD4 total memory cells (1.5% at day 0 pre-dose to 3.5% at day 7, ~2-fold, p=0.005) were also observed, but at a lower percentage and fold change than seen for ICOS positivity among CD4 total memory cells. No increases in the percentage of ICOS and PD-1 positive total memory cells were observed for vehicle-treated animals. Interestingly, the increase in the percentage of ICOS+ total memory cells observed for MEDI6383 was not seen for MEDI6469, whilst the fold increase in PD-1+ CD4 total memory cells was higher for MEDI6469 (1% at day 0 pre-dose to 5% at day 10, ~5-fold, p=0.04) than for MEDI6383. Enhanced cytokine production may also be an indicator of T cell co-stimulation following OX40 agonism, as shown in vitro. However, neither intracellular nor plasma levels of cytokine were measured in this study.

Examining B cell proliferation, MEDI6383 induced an increase in the percentage of circulating Ki67+ B cells (10% at day 0 pre-dose to 24% at day 17, ~2 fold, p=0.01), reaching a maximum proliferation later (Day 17) than that observed for proliferating CD4 and CD8 total memory cells (Figure 6D). MEDI6383 induced a similar fold increase of proliferating B cells as compared to MEDI6469 (8% at day 0 pre-dose to 16% at day 14, ~2-fold, p=0.05).

MEDI6383 and MEDI6469 treatment initially resulted in a decrease in absolute numbers of circulating CD4 T and B cells per mL of blood as measured at day 4 post dose, consistent with driving an exodus of CD4 T and B cells from the circulation. This was followed by increases in CD4, CD8 T cell and B cell absolute numbers over the second week indicating that the observed rise in percent Ki67 positive cells were associated with increases in circulating cell numbers (Supplementary Figure 10).

Discussion

Within the TME, an endogenous anti-tumor T cell immune response is shaped by a number of signaling events. First, effective presentation of tumor-specific epitopes by tumor cells or antigen-presenting cells provides an essential signal for T cell activation. Secondary, co-stimulatory signals such as that provided by OX40 promote effector T cell activation and expansion, as well as the generation of effector and central memory T cells required for long-lived anti-tumor immunity.

As a therapeutic strategy for the treatment of cancer, MEDI6383 was engineered to promote an anti-tumor immune response through potent stimulation of OX40. Based on the biology of OX40 engagement, we hypothesized that MEDI6383 would enhance T cell co-stimulatory signaling, resulting in pro-inflammatory cytokine release and proliferation in the context of a T cell receptor stimulus. Furthermore, we hypothesized that the drug would expand memory T cells and provide protection of conventional, activated T cells from the inhibitory effects of regulatory T cells. Finally, we hypothesized that OX40 engagement would induce anti-tumor specific immunity dependent on T cells.

With regard to T cell activation, we found that MEDI6383 in solution phase induced the activation of the NFκB promoter in OX40-positive reporter T cells, and that this activity was greatly enhanced by FcγR clustering of the fusion protein. In vivo, cells that express FcγRs would be expected to cluster MEDI6383 and thus drive OX40 co-stimulation. We found that primary human tumors, including NSCLC and renal cell carcinoma (RCC), contained immune cells expressing FcγRs, and these cells effectively clustered MEDI6383 and mediated potent OX40 reporter activity ex vivo. As expected, reagents that have the potential to strongly block Fc:FcγR interactions, such as control hexamer fusion proteins of the IgG1 or IgG4P isotypes used in molar excess or anti-FcγR antibodies, interfered with MEDI6383 bioactivity mediated by FcγR-expressing cells. However, the bioactivity was not affected by human IgG at >400 times molar excess of MEDI6383 nor as strongly by human serum that contains high levels of human IgG. The latter demonstrates the ability of MEDI6383 as a hexameric IgG-containing fusion protein to out-compete endogenous IgG for FcγR binding and clustering of drug, a feature that is important to consider when MEDI6383 is administered in vivo where endogenous IgG levels will be high.

In vivo, we used a human tumor/immune cell admixed model in NOD/SCID mice to demonstrate T cell-dependent tumor eradication by MEDI6383. Although not examined in this study, such tumors would be expected to be infiltrated with FcγR-expressing mouse immune cells, and these potentially could have mediated clustering of MEDI6383. It is anticipated that FcγR-positive immune cells, which may include myeloid cells, dendritic cells, or B cells, will be important in human tumors and tumor draining lymph nodes of patients to potentiate MEDI6383-mediated anti-tumor activity. However, some activity related to OX40 clustering by the hexameric OX40L fusion protein itself without further immobilization on cell surfaces cannot be ruled out.

The CD64 FcγR has relatively high affinity for IgG4, whereas the FcγRs CD32 and CD16 have relatively lower affinity (16). We determined the equilibrium binding (K_D) values for MEDI6383 binding to human FcγRs by surface plasmon resonance (Supplementary Table 3) and found expected low, micromolar affinity binding to CD16 and CD32A and CD32B, and higher, nM affinity binding to CD64. CD64 (FcγRI) and CD32A or B (FcγRII isoforms) enhanced drug activity through clustering, but CD16 (FcγRIII) lacked this enhancement. Based on the measured affinities, it is not clear why CD32A and CD32B would enhance clustering and bioactivity whereas CD16 would not. It is important to note that the CD32A or CD32B were expressed at high levels in our HEK expressing or Raji 2-cell bioassays, and may explain why these FcγR-presenting cells demonstrated activity despite their relatively low affinity for IgG4. However, the lack of effective clustering by CD16, despite its robust expression in HEK cells, was consistent with its relatively low affinity for IgG4 and our finding that MEDI6383 did not mediate measurable NK cell-mediated ADCC of OX40-expressing activated T cells. In contrast, a human IgG1 version of the OX40L fusion protein with stronger binding to CD16 mediated potent ADCC of OX40-expressing T cells. Likewise, MEDI6383 did not bind to the complement component C1q as did a human IgG1 control antibody. Thus, MEDI6383 would not be expected to mediate complement-dependent cellular cytotoxicity of OX40-expressing cells. The lack of NK cell effector function for MEDI6383 was specifically engineered by incorporation of the IgG4 isotype, and was designed to prevent the elimination of activated, tumor-reactive effector T cells in the TME through NK cell mediated ADCC or by CDC. Whether MEDI6383 may mediate other effector functions through FcγRs, such as antibody-dependent cellular phagocytosis (ADCP) or ADCC mediated by FcγR-expressing immune cells other than NK cells, remains an area for further investigation.

In line with the observed NFκB activation in reporter cells, immobilized MEDI6383 induced Th1 and Th2 cytokine release and cellular proliferation in pre-activated primary human CD4 T cells. The cytokine release profile induced by OX40 agonism during an anti-tumor immune response likely depends on the local cellular and cytokine milieu, and may include a mixed Th1/Th2 response (17) as observed here. The activity of MEDI6383 required concomitant TCR signaling, as the fusion protein was inactive in the absence of an anti-CD3 mAb used to stimulate the TCR. Likewise, consistent with the relatively low NFκB promoter activity observed in reporter cells treated with MEDI6383 in solution phase, activated primary human CD4 T cells only showed evidence of cytokine release and proliferation by clustered, but not solution phase, MEDI6383. Together, these results suggest that MEDI6383 may only induce T cell activation in the presence of a TCR stimulus, and will likely have optimal activity when clustered. The enhancement of TNFRSF agonist clustering by FcγRs for drug activity is not unique to MEDI6383 (18), and is likely a common phenomenon for agonists whose target receptors are multimerized by natural ligands as is the case for the OX40:OX40L interaction. As shown by the example in Supplementary Figure 4, primary human tumors may be infiltrated by FcγR-expressing human myeloid cells, and we anticipate that these cell types will mediate MEDI6383 clustering in the tumor.

In addition to enhancing the activation of conventional CD4 T cells, OX40 agonism of these cells has been reported to protect them from the immunosuppressive effects of Treg cells (19,20). The expression of OX40 on the surface of Treg cells themselves in human tumors has been found to be high (21). As mentioned above, MEDI6383 was engineered to reduce or eliminate ADCC function, and so would not be expected to mediate cell killing of OX40+ Treg. However, MEDI6383 may modulate Treg formation or function in different ways. For example, OX40 engagement on Tregs has been alternatively reported to promote Treg cell death (22), prevent the formation of FoxP3+ Treg (23,24), reduce FoxP3 expression and alter the suppressive capacity of Treg (25–27), and even to induce Treg expansion under certain experimental conditions (17,28). In this study, we showed that MEDI6383 restored the proliferation of activated, conventional CD4 Teff cells in the presence of immunosuppressive natural regulatory T cells to a level observed when conventional CD4 Teff cells were cultured in the absence of Treg. Whether this effect may occur through engagement of OX40 on nTreg to abrogate their suppressive function or on conventional T cells to protect them from the immunosuppressive effects of regulatory T cells remains to be determined, and is an area of current investigation. Immune cells other than regulatory T cells, such as suppressive myeloid cells or tumor-associated macrophages, may also mediate immunosuppression in the TME. Whether MEDI6383 may overcome some of the immunosuppression mediated by these cell types is also an area for further study. In this study, MEDI6383 also induced the proliferation of Treg cells, either alone or in co-culture with Teff cells. As mentioned above, this is consistent with other published reports (17,28). MEDI6469, an agonist murine anti-human OX40 mAb, expanded conventional CD4 T cells but did not demonstrate Treg cell expansion in the peripheral blood of subjects with advanced malignancies treated with the drug; however, whether MEDI6383 may induce Treg expansion in the peripheral blood or tumors of patients remains to be seen. Results reported here, however, indicate that MEDI6383 would likely enhance Teff function in the presence of Treg cells in either case.

The anti-tumor activity of MEDI6383 was demonstrated in an allogeneic human T cell:tumor cell admixed model in NOD-SCID immunodeficient mice. In this model, MEDI6383 inhibited the growth of A375 human melanoma tumors in a T cell-dependent manner. The effectors of this activity are likely cytolytic granzyme and perforin granules released by activated T cells, although cytotoxic or cytostatic activity mediated by cytokines and Fas or TRAIL ligands cannot be ruled out and deserve further study.

In addition to enhancing the activation and proliferation of conventional effector T cells, OX40 agonists have been shown to promote the survival and expansion of memory T cell subsets (29,30). In particular, administration of OX40 agonists to tumor-bearing mice expands memory T cells and establishes an anti-tumor memory T cell response that can provide long-lasting anti-tumor immunity (31). To test the hypothesis that MEDI6383 is capable of expanding memory T cells, we studied the pharmacodynamic effects of MEDI6383 administered intravenously to healthy untreated rhesus macaques. Immunophenotyping of peripheral blood T cells in a clinical trial of MEDI6469 in patients with advanced malignancies demonstrated activation and proliferation of CD4 and CD8 T cells in the peripheral blood of treated patients (4). In this study, MEDI6469 likewise induced T cell proliferation and increased absolute CD4 and CD8 T cell numbers in the peripheral blood of rhesus macaques, justifying the use of this species as a relevant model to study MEDI6383-mediated pharmacodynamic activity.

Results from the rhesus study showed that MEDI6383 induced the proliferation of both CD4 and CD8 Tcm and Tem, but not naïve T cells that have low OX40 expression. The effects were particularly potent with respect to the induction of CD4 Tcm proliferation. This bias towards CD4 was not unexpected as the upregulation of cell surface OX40 on activated CD4 T cells is much higher than that on activated CD8 T cells, where expression levels of OX40 are relatively modest. Consistent with this, we found that isolated CD8 cells activated in vitro respond poorly to OX40 agonists compared to isolated, activated CD4 T cells. However, CD8 T cells among enriched CD3 T cells (CD4 + CD8) have sometimes demonstrated modest proliferative responses to MEDI6383 and both cell populations demonstrated increased cell surface activation marker expression, consistent with a helper cytokine effect from CD4 helper T cells (Th) in the co-culture or resulting from low-level OX40 expression on CD8 T cells. The activation of CD4 T cells may have contributed to the proliferation of CD8 T cells in MEDI6383-treated rhesus monkeys, although this is difficult to formally distinguish from direct effects on CD8 T cells expressing low OX40 levels.

Interestingly, we found that Tcm proliferated to a much greater extent than the Tem subset, and the peak proliferation in the latter was delayed relative to the former. This suggests that rhesus Tcm cells may be more responsive to OX40 signals, and/or they may themselves subsequently promote proliferation of Tem cells or convert into a Tem-like phenotype upon encounter with cognate antigen (32). However, the delayed appearance of Tem proliferation could simply reflect a delayed kinetics of proliferation in this T cell subset relative to that of Tcm cells. The interplay and interconversion of memory T cell subsets, and their respective proliferation kinetics, in animals treated with OX40 stimulating drugs remains an area of further study. However, given that anti-tumor Tcm cells may provide more persistent and effective anti-tumor immunity (33) and that OX40 agonism may potentiate memory phenotypes while preserving cytolytic effector function (34), this will be of particular interest in the context of long-lasting anti-tumor immunity that may be generated by MEDI6383 in the treatment of cancer.

The initial decrease in absolute numbers of circulating CD4 and CD8 T cells and CD20+ B lymphocytes observed in MEDI6383-treated non-human primates are interesting as they are consistent with the possibility that peripheral blood T cells are being mobilized to exit the circulation on initial exposure, although other hypotheses may need to be considered. A decrease in absolute lymphocyte count within the first week after the administration of checkpoint blocking mAbs has been observed in human clinical trials (35), and so this may be a general phenomenon after pharmacological activation of peripheral lymphocytes. In this study, reductions of CD4 and CD8 T cell numbers in the peripheral blood were short-lived. Generally, T cell counts increased in the second week post treatment, the same timeframe in which increases in T cells entering the cell cycle measured by Ki67 expression were observed. Whether these blood changes had corresponding changes in tissues and lymph nodes is an interesting question but was not addressed in this study.

Consistent with the induction of T cell proliferation and in vitro enhancement of cell surface T cell activation markers such as PD-1 and CD25 by MEDI6383, the up-regulation of the activation markers ICOS and PD-1 were observed among memory CD4 and CD8 T cells. The peak induction of ICOS was higher than that of PD-1, and higher in CD4 than CD8 total memory T cells. Interestingly, CD25 induction was not observed in vivo, and the induction of PD-1 was surprisingly low considering the levels of T cell activation as indicated by Ki67 and ICOS levels. In general, ICOS+ or PD-1+ cells were observed in a much smaller fraction of T cells relative to Ki67+ (proliferating) T cells. This may reflect the induction of these markers in a subset of proliferating cells, or a difference in the kinetics of their expression, resulting in lower steady-state percentages of ICOS and PD-1 positive cells relative to Ki67 positive cells that reflect cells outside of G_0 in the cell cycle. In any case, up-regulation of these activation markers further supports the idea that OX40 agonists such as MEDI6383 may combine well in cancer treatment with checkpoint inhibitors such as PD-1/PD-L1 as suggested by mouse syngeneic tumor models (36,37). Clinical trials with OX40 agonists combined with PD-1/PD-L1 therapies are ongoing, including MEDI6383 combined with the anti-PD-L1 mAb durvalumab (NCT02221960).

MEDI6383 was found to induce B cell proliferation (Ki67 positivity) in addition to T cell proliferation. As resting and activated rhesus B cells do not express OX40, this would appear to be an indirect effect of MEDI6383 on B cells. It is possible that MEDI6383 activated CD4 follicular helper T (Tfh) cells within lymph node germinal centers, leading to the maturation and proliferation of rhesus B cells. Some evidence suggests that OX40 is expressed by Tfh cells and that engagement of OX40 promotes Tfh cell activity with regard to B cell expansion (38). Such an effect of MEDI6383 on B cell expansion may be meaningful in patients with tumors, and in fact increased antibody titers in vaccinated NHP (39) and cancer patients (4) following MEDI6469 treatment have been observed, suggesting B cell activation in those settings. Potentially, activation and expansion of B cells producing antibodies that recognize tumor neoantigens may induce direct NK cell-mediated tumor lysis and/or opsonization and phagocytosis (antibody-dependent cellular phagocytosis) by professional phagocytic cells within the TME. Each of these processes may contribute to anti-tumor activity of OX40 agonists. In contrast, regulatory B cells within a TME or in surrounding tertiary lymphoid structures may act to suppress anti-tumor specific T cell responses, which would serve to oppose anti-tumor T cell activity. An expansion of regulatory B cells by OX40 agonists could theoretically oppose anti-tumor immunity. Given the potential pro- and anti-tumor roles played by B cells, the effects of MEDI6383 on B cell form and function remains a subject of particular interest. The effects of MEDI6383 on B cell activation should also be interpreted with caution, however, as anti-drug antibodies are frequently observed in non-human primates administered with antibodies or recombinant fusion proteins. Such responses may indicate a non-specific B cell activation in response to the drug and are difficult to discern from specific B cells effects since isotype control proteins would also be expected to induce similar ADA responses. Therefore, the true impact of MEDI6383 on B cell activation may await results from studies in human subjects where ADA responses may be less common than those observed in non-human primates.

In summary, we found that MEDI6383 was a strong activator of T cells in vitro and in vivo, leading to proliferation of effector and memory T cells and protection from Treg-mediated suppression. The activity depended upon concomitant TCR signaling, and was substantially enhanced by FcγR-mediated clustering. As expected, MEDI6383 lacked OX40-directed ADCC effector function. These properties, coupled with the ability to expand memory T cells, makes MEDI6383 an attractive candidate to induce durable anti-tumor immunity in patients with cancer. MEDI6383 is currently undergoing testing in patients with advanced solid malignancies, both as monotherapy and in combination with the anti-PD-L1 blocking mAb durvalumab (NCT02221960).

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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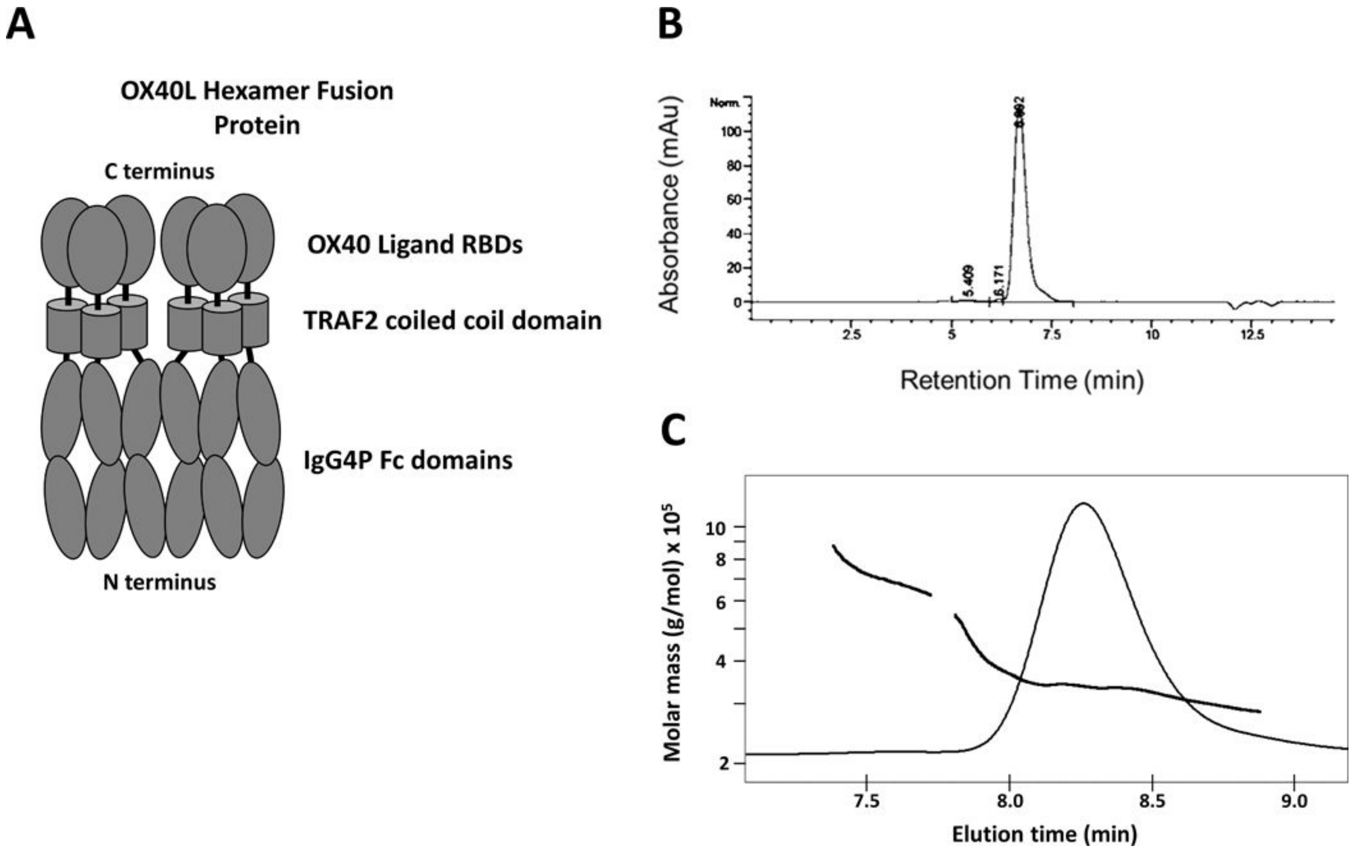

Figure 1.

Schematic diagram of the proposed structure of MEDI6383. Figure 1 shows that MEDI6383 is a human OX40 ligand IgG4P Fc fusion protein consisting of three subunits containing an OX40L receptor binding domain (RBD), a TRAF2 coiled coil domain, and an IgG4 Fc domain containing an S→P mutation at position 228 according to EU numbering of the full length IgG4 heavy chain sequence to prevent inter-Fc strand exchange. (A) The proposed structure of the protein product is a hexameric "dimer of trimers". The OX40L RBDs are oriented from N-terminal amino acids (top) to the C-terminus (bottom) as indicated. (B) Analytical Size Exclusion Chromatography (SEC) analysis of intact MEDI6383 showed highly monomeric (> 98%) single peak with very low levels of aggregates, no fragments or free chains. (C) SEC combined with Multi-Angle Light Scattering (SEC-MALS) showed an apparent molecular mass of approximately 330,000 daltons which supports the proposed hexameric form. Light trace spanning entire elution time, MEDI6383 sample; darker trace, molecular mass standards.

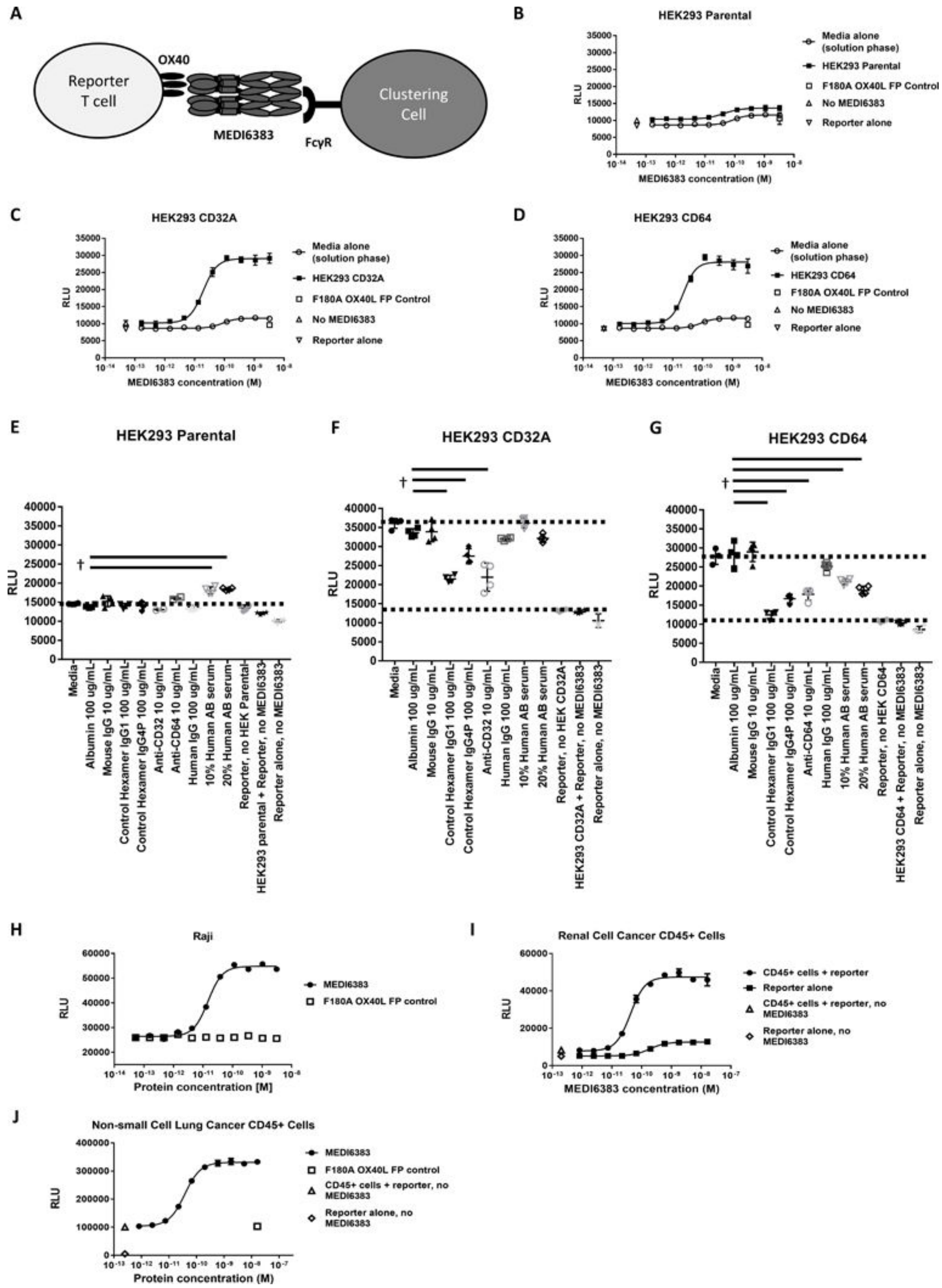

Figure 2.

OX40 reporter bioactivity of MEDI6383. Figure 2 shows the bioactivity of MEDI6383 using OX40-expressing Jurkat NFκB reporter cells with or without clustering by FcγRs expressed on human cells. (A) Schematic illustration of the anticipated interactions in a 2-cell bioassay using FcγR-expressing drug “clustering” cells and the NFκB-luciferase reporter Jurkat T cell line that expresses OX40. (B) Concentration-dependent response of MEDI6383-mediated activation of an NFκB-luciferase reporter Jurkat T cell line by MEDI6383 in solution phase or in the presence of parental HEK293 cells lacking FcγR expression. F180A

OX40L FP control or no MEDI6383, as indicated, were incubated with HEK293 plus reporter cells as controls. As an additional control, reporter cells were incubated in the absence of HEK293 cells and MEDI6383 (Reporter alone). (C) Bioactivity of MEDI6383 clustered by CD32A-expressing HEK293 or (D) CD64-expressing HEK293 cells compared to MEDI6383 in solution phase or to controls, as indicated. (E-G) Effects of various FcγR blocking reagents, or controls, on the bioactivity of 0.5 μg/mL (1.6 nM) of MEDI6383 incubated with parental or FcγR-transduced HEK293 plus reporter cells, as indicated. Upper dotted line indicates mean activity of MEDI6383 without blocking reagent (media) plus HEK293 cells and lower dotted line represents mean activity of reporter cells incubated with MEDI6383 in the absence of HEK293 cells. †, $p<0.001$ by one-way ANOVA comparing the indicated tests to either media, albumin, or mouse IgG control proteins. (H) Bioactivity induced by MEDI6383 or the F180A OX40L FP control protein clustered by the CD32B-expressing Raji B cell tumor line. (I) Bioactivity observed after MEDI6383 clustering by CD45 immune cells isolated from a resected primary human renal cell cancer or (J) a resected primary human non-small cell lung cancer. Results are representative of at least 3 independent experiments with data points and error bars representing the mean and standard error of the mean (SEM), respectively, of triplicate measurements, with the exception of results from CD45 cells isolated from primary human cancers which represent individual experiments.

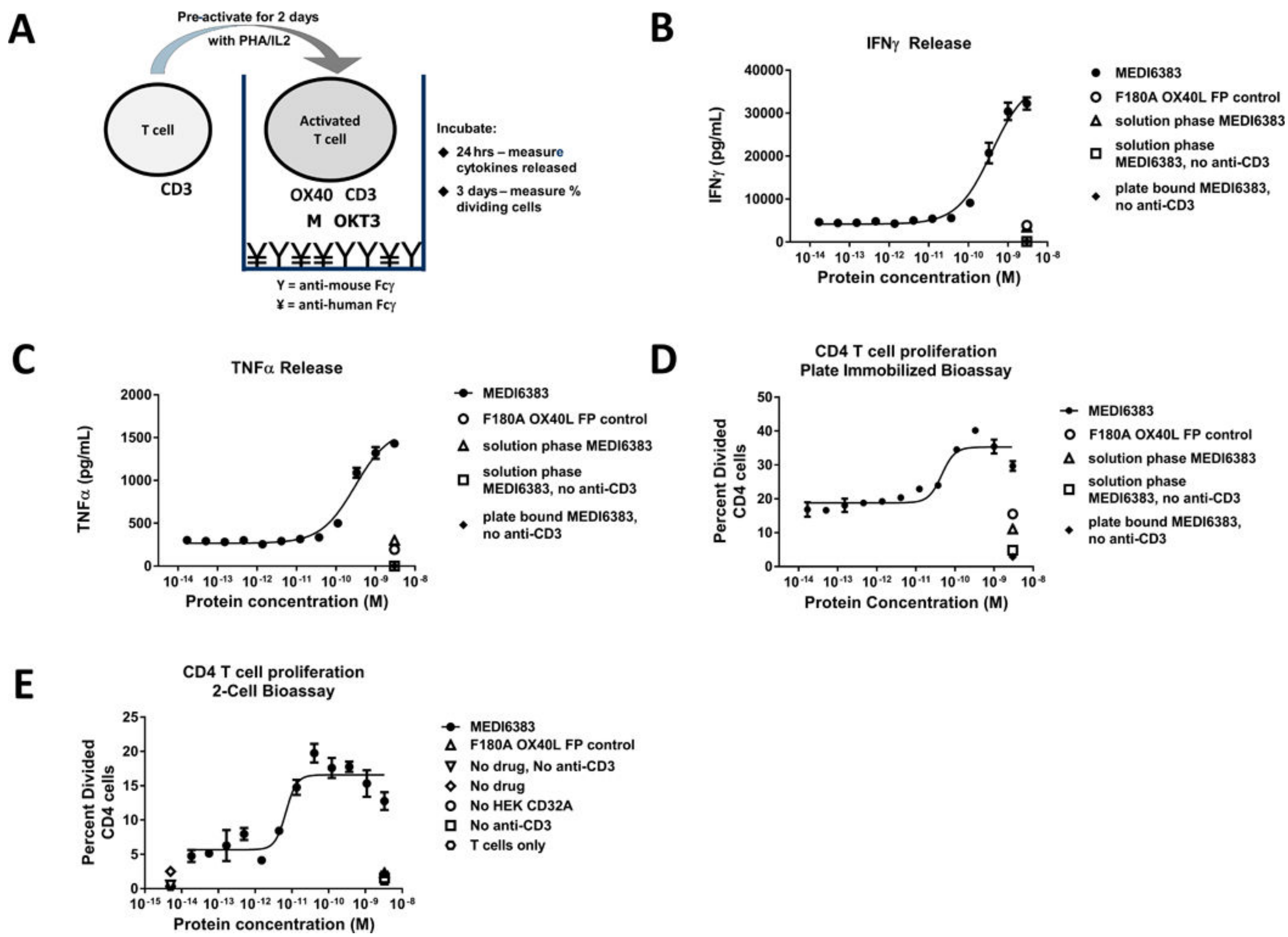

Figure 3.

Activity of MEDI6383 using primary human T cells. Figure 3 shows the activity of MEDI6383 immobilized to tissue culture plastic or clustered by CD32A-expressing cells with OX40-expressing activated primary human T cells. (A) Schematic illustration of the bioactivity assay using plate immobilized MEDI6383. (B) IFNγ and (C) TNFα release into cell culture supernatants and (D) proliferation of cells plated under the conditions described next to each graph. Solution phase MEDI6383 indicates drug added to medium instead of captured on the plate surface, and no anti-CD3 indicates omission of anti-CD3 mAb clone OKT3 stimulation in the wells. (E) Bioactivity of MEDI6383 with OX40-expressing activated primary human CD4 T cells co-cultured with CD32A-expressing HEK293 cells and a sub-optimal amount of anti-CD3 mAb clone OKT3. No drug, no anti-CD3, and no HEK CD32A indicate bioassay conditions containing all components except MEDI6383, anti-CD3 mAb clone OKT3, or CD32A-expressing HEK293 cells, respectively. T cells only indicate the presence of CFSE-labeled CD4 T cells alone in the absence of drug, anti-CD3 mAb clone OKT3, and CD32A expressing HEK293 cells. Results for plate-immobilized or HEK CD32 clustered MEDI6383 are each representative of 3 independent experiments, with data points and error bars representing the mean and SEM of triplicate measurements, respectively. M, molarity.

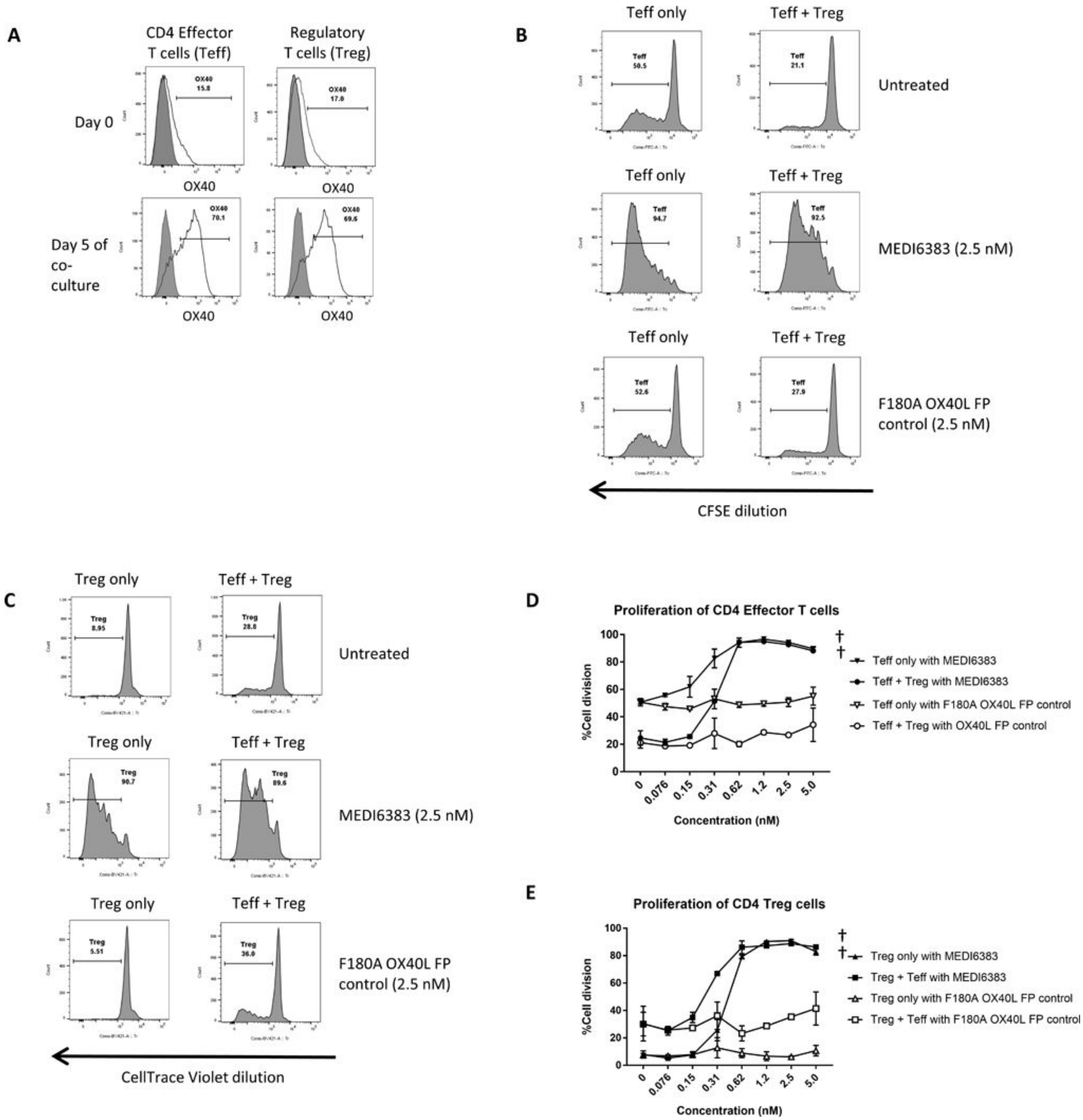

Figure 4.

MEDI6383 overcomes the suppressive activity of nTreg cells. Figure 4 demonstrates the ability of MEDI6383 to reverse the immunosuppressive activity of nTreg co-cultured with Teff. (A) Expression of cell surface OX40 by Treg cells at the time of isolation (Day 0) and after 5 days of Teff/Treg co-culture in the presence of anti-CD3 and anti-CD28 stimulation. (B) Examples of CFSE dilution of Teff cells or (C) Treg among untreated, MEDI6383-treated, or F180A OX40L FP control-treated Teff cell, Treg cell, or Teff/Treg co-cultures, as indicated. (D) Plot of CD4 Teff cell proliferation versus concentration of MEDI6383- or

F180A OX40L FP control-treated Teff cell (Teff only) or Teff/Treg co-cultures (Teff + Treg), as indicated. (E) Plot of CD4 Treg cell proliferation versus concentration of MEDI6383- or F180A OX40L FP control-treated Treg cell (Treg only) or Teff/Treg co-cultures (Teff + Treg), as indicated. Data is representative of 3 independent experiments. Points and error bars represent mean of triplicate measures and standard error of the mean, respectively. † $p<0.05$ using two-tailed Student's t-test comparing MEDI6383-treated versus F180A OX40L FP control-treated cells for points 0.15 nM and above for Teff + Treg and 0.62 nM and above for Teff only in (D) and for points 0.31 and above for Teff + Treg and 0.62 nM and above for Treg only in (E).

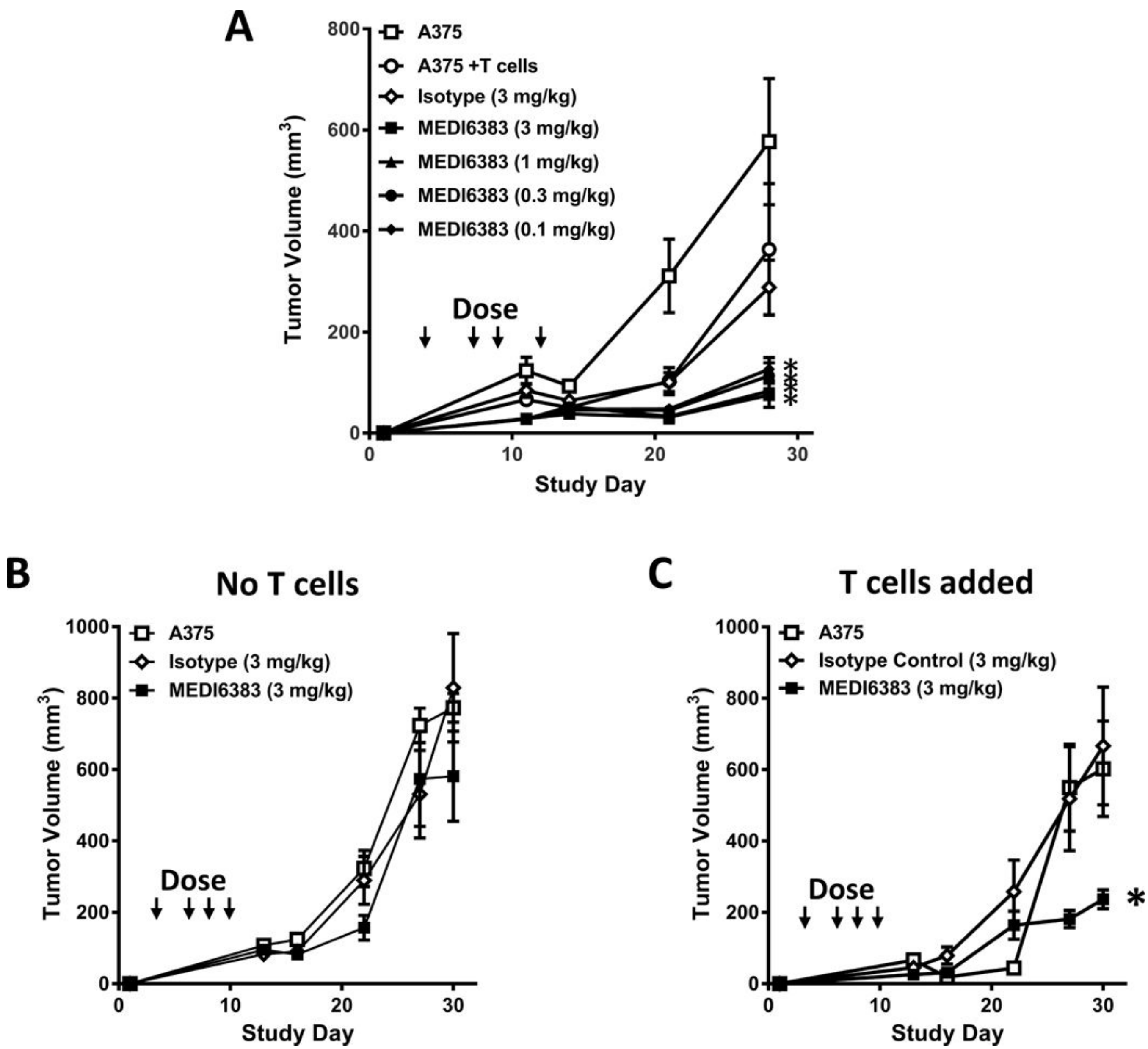

Figure 5.

Anti-tumor activity of MEDI6383. Figure 5 demonstrates the T cell dependent activity of MEDI6383 in a human T cell/tumor cell admixed model in NOD/SCID mice. (A) Statistically significant tumor growth inhibition by MEDI6383 administered over a range of dose levels in mice engrafted with human A375 melanoma tumor cells admixed with allogeneic A375-reactive human CD4 and CD8 T cells. (B) Lack of MEDI6383 activity in mice engrafted with A375 tumor cells but in the absence of human T cells. (C) Activity of MEDI6383 when allogeneic A375-reactive human T cells were engrafted with A375 tumor cells. *, $p<0.05$ by Mann-Whitney rank sum test of mean tumor size at day 28 for MEDI6383 treated groups compared to isotype control group. Arrows indicate times after tumor injection when MEDI6383 was administered to mice. Statistically significant differences in mean tumor size between MEDI6383 and isotype control group was demonstrated in three independent experiments, with representative data shown.

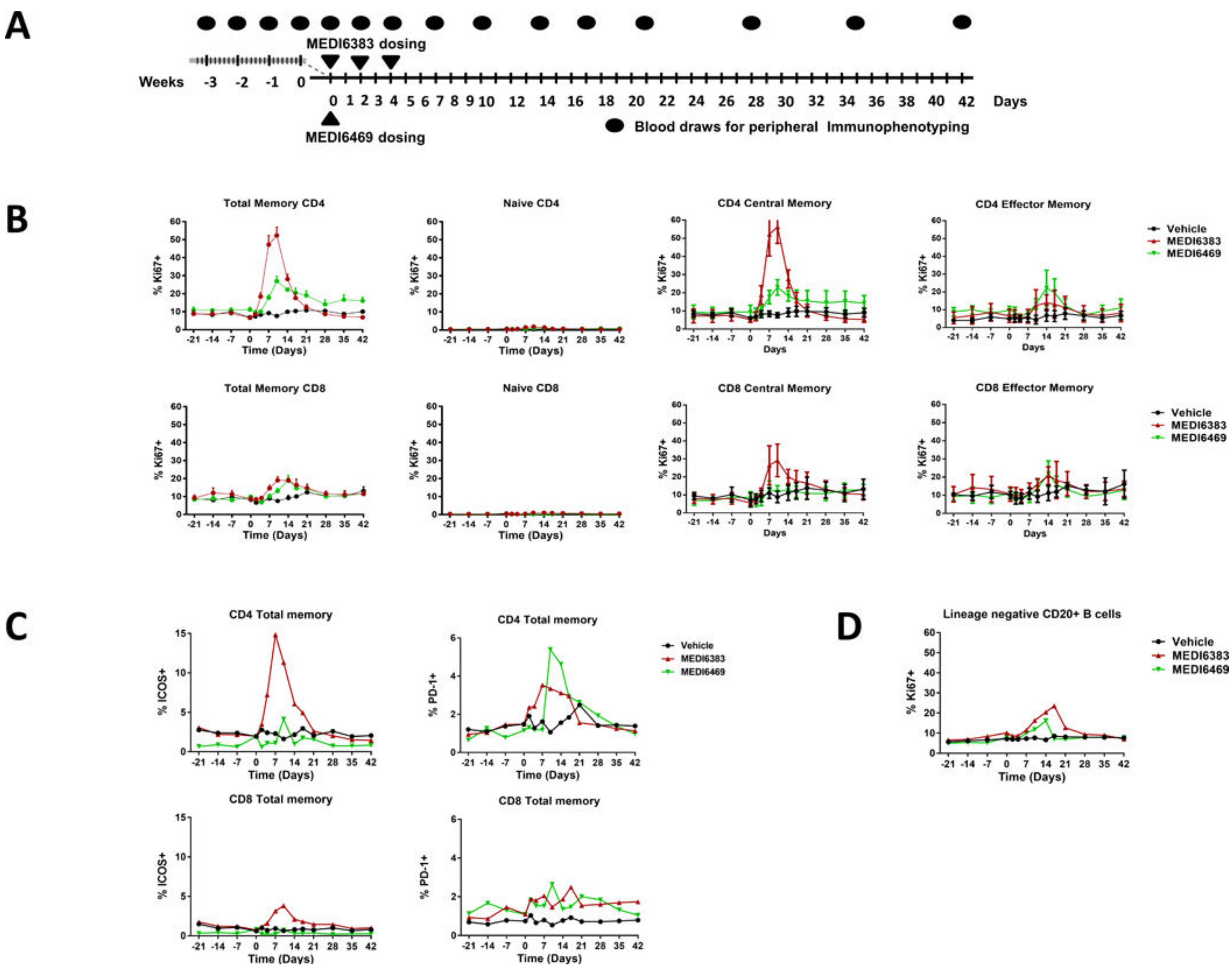

Figure 6.

Pharmacodynamic effects of MEDI6383. Figure 6 shows the activity of MEDI6383 on peripheral T and B cells when administered to healthy rhesus macaques. (A) Schematic for test article dosing and blood draws for immunophenotyping by flow cytometry. (B) Percentage of Ki67+ CD4 (top) and CD8 (bottom) total memory, naïve, central and effector memory T cells, as indicated, prior to and after test article dosing on day 0. (C) Percentage of ICOS+ (left) and PD-1+ (right) total memory CD4 (top) and CD8 (bottom) T cells. (D) Ki67+ CD20 B cells. Error bars were withheld for (C) and (D) so that the comparisons between different treatments could be more easily visualized.